The Neoproterozoic-Early Paleozoic tectonic evolution of the South China Block: An overview

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Abstract. This paper gives a brief review of what I consider as the state of the art regarding the largely accepted data and ideas concerning the Proterozoic to Early Paleozoic tectonic evolution of South China. The South China craton was built by the welding of the Yangtze and Cathaysia blocks, with a different previous history giving a different pre-Neoproterozoic basement composition, due to the Jiangnan (Jinning, Sibao) orogeny. This Jiangnan orogeny was a collisional event, induced by the consumption of an intervening oceanic domain by subduction beneath the Yangzte plate. The evolution involved a volcanic arc on the Yangtze active margin, active from ca. 980 Ma to ca. 850 Ma, the subsequent collision beginning at around 870-860 Ma and responsible for the emplacement of thrust sheets of ophiolitic mélange (dated around 1000-900 Ma) and blueschists (900-870 Ma), followed by late- to post-collisional granitic plutonism (840-800 Ma). The newly amalgamated South China craton suffered from rifting, starting around 850 Ma, marked by mafic-ultramafic magmatism until ca. 750 Ma. The Nanhua rift basin evolved with a thick sedimentation in its middle part until the Ordovician. South China was affected by the early Paleozoic orogeny (mainly Silurian), characterized by a strong quasi-symmetrical intracontinental shortening, involving the sedimentary cover of the rift and its margins as well as the basement, leading to crustal thickening. This crustal thickening induced an important anatexis and emplacement of peraluminous granites during the Silurian. Unlike the Jiangnan orogeny, which was of collisional type, the Early Paleozoic one was a bit similar to a Pyrenean intracontinental type. Some pending problems need further research for clarification, for example: the location and timing of integration of South China within Rodinia, the triggering factor of the Early Paleozoic orogeny, the mapping of the contacts bounding the Lower Paleozoic thrust sheets responsible for the crustal thickening.

Keywords South China, Yangtze block, Cathaysia block, Jiangnan orogeny, Early Paleozoic orogeny, tectonic evolution.

1. Introduction

The Asian continent was formed by the amalgamation of several major blocks (e.g. Chen et al., 1993; Ren et al., 1999, 2012). One of them is the South China Block. It is generally accepted that this block is in turn composed of two main tectonic units: the Yangtze block to the north and the Cathaysia one to the south (Fig. 1). The present boundary between the Yangtze Block and Cathaysia is a big fault: the Yichun-Shaoxing fault (Wang, 1986; Zhao and Cawood, 1999). Although the Jiangnan (or Sibao) belt, on the southern border of Yangtze Block (Fig. 1), is now commonly regarded as the result of the welding of the two blocks, the precise age and geodynamic interpretation of this Jiangnan orogeny, as well as the later evolution during the Phanerozoic, especially the Early Paleozoic, have been subject of big debates until the last decade (e.g. review in Charvet et al., 1996, 2010).

Although the Triassic and Cretaceous events reworked the South China area (e.g. Li, 1998; Xiao and He, 2005; Li and Li, 2007; Shu et al., 2008a, 2009, 2012; Lepvrier et al., 2011; Shu, 2012), this paper will deal with the Precambrian and Early Paleozoic history, reviewing the main ideas now advocated for this evolution and raising some pending questions deserving further research.

2. Two distinct Precambrian Blocks

The basement of the Yangtze and Cathaysia blocks that form the South China craton (Fig. 1) both experienced a different evolution during the Precambrian.

The Yangtze block comprises Neo-Archean metamorphic rocks, but the outcrops of pre-Neoproterozoic basement rocks are rare, appearing sporadically in Yunnan, Guizhou, and Hubei. It shows an old core consisting of granitic gneiss of ca. 2.90–2.95 Ga in its northern part, with the oldest being the Kongling complex near the Yangtze Gorge Dam, comprising Archean to Paleoproterozoic high-grade metamorphic TTG (tonalite, trondhjemite and granodiorite) gneisses, metasedimentary rocks and amphibolites (e.g. Gao et al., 1999; Qiu et al., 2000; Zhang et al., 2006; Yu et al., 2008). The Archean basement is also detected beneath Proterozoic upper-crustal rocks (Zheng et al., 2006). Within the latter, the lower part (Lengjiaxi Group) once considered as Mesoproterozoic is in fact mostly Neoproterozoic, according to SHRIMP datings, with a top limit at 0.82Ga (Gao et al., 2008, 2010, 2011). The Neoproterozoic strata are, in ascending order, divided into the Lengjiaxi Group (1.0?-0.82Ga), Banxi Group (0.82—0.75Ga), Nanhuan System (0.75-0.635Ga) and Sinian (Ediacaran) System (0.635-0.542Ga) (Ren et al., 2012). The dating of the top boundary of the Lengjiaxi Group at 0.82Ga suggests that the basement of the Yangtze craton was formed 0.2 Ga later than the Rodinia supercontinent (Ren et al., 2012).

In the Cathaysia block the basement metamorphic rocks, most of which are Neoproterozoic to early Paleozoic in age, are mainly found in the northeastern part (southern Zhejiang – northern and western Fujian – eastern Jiangxi, i.e.Wuyishan area), in the central part (Nanling Mts), and the southwestern part (Yunkai area) (Fig. 1). The Precambrian basement is also partially present in the area (Nansha) of the southern China sea and eastern China sea (Ren and Chen, 1989; Ren et al., 1990) forming a South China sea-East China sea block (Shu, 2012). The oldest rocks in Cathaysia are about 1.9–1.8 Ga in age and are limited to the southern Zhejiang-northwestern Fujian area (Hu, 1994; Gan et al., 1995; Yu et al., 2009) and Nanling area (Yu et al., 2009; Yao et al., 2011). But the analysis of detrital zircons from Ordovician-Devonian sandstones of southern Jiangxi suggests the presence of Archean basement of ca. 2.46 Ga age (Yao et al., 2011). If the Neoproterozoic rocks (schist and gneiss) are widespread, the Mesoproterozoic ones are very rare. However, in detail, the Precambrian crust of the Cathaysia Block can be divided into two distinct tectonic domains, the Wuyishan terrane to the northeast and the Nanling-Yunkai terrane to the southwest; the basement rocks of the two terranes are comprised of different components. The Wuyishan terrane is characterized by dominant Paleoproterozoic (1.86 Ga) and lesser Neoarchean magmatism. In contrast, the Nanling-Yunkai terrane contains abundant Neoarchean and Grenvillian zircons, some evidence of Mesoproterozoic activity and rare Paleo- to Meso-Archean and Neoproterozoic zircons (Yu et al., 2010).

The sedimentary cover goes from the Nanhua system (0.75—0.635Ga, Ren et al., 2012) to the Ordovician, before the Devonian unconformity.

Therefore the two blocks seem to have been constructed of different Precambrian crustal components. They could be juxtaposed only after ca.1.0 Ga (Chen et al., 1991; Li et al., 1994; Shi et al., 1994; Shu et al., 1995, 2006, 2011; Charvet et al., 1996; Li, 1999; Wang et al., 2006, 2007a; Yu et al., 2008).

3. The collisional welding of Yangtze and Cathaysia Blocks

Through time, the formation of the South China Block by welding of the Yangtze and Cathaysia Blocks was controversial. It was still a hot matter of debate in the 1990s, as recorded in Charvet et al. (1996). Some authors (e.g. Ren, 1991) argued for a unique block since the Early Precambrian, without any suture zone in it. Since the 1980s, however, the Jiangnan belt (Fig. 1) was considered as the result of the amalgamation of the Yangtze and Cathaysia blocks (Guo et al., 1980, 1985) but the advocated timing and process varied: collisional events in the Middle-Late Proterozoic (Guo et al., 1980, 1985; Rowley et al., 1989; Chen et al., 1991), early Neoproterozoic ca. 900 Ma (Guo et al., 1989; Chen et al., 1991; Xu et al., 1992; Shu et al., 1994; Shu and Charvet, 1996; Charvet et al., 1996; Li, 1998; Ye et al., 2007; Li et al., 2008a; Chen et al., 2009); Ordovician-Silurian (Haynes, 1988), and Late Paleozoic-Mesozoic (Hsü et al., 1988, 1990; Li, 1998; Xiao and He, 2005; Li and Li, 2007).

But recent works documented the age of amalgamation to be Neoproterozoic and most researchers now believe that the two blocks amalgamated during the Proterozoic Sibao orogeny (also called the "Jiangnan" or "Jinning" orogeny in the literature). However, several processes were proposed, differing in details, and the tectonic calendar varies according to authors; so the timing and evolution of this orogeny are still controversial. In general, the main geodynamic scheme is admitted by authors: an oceanic closure, during the Neoproterozoic, after a northward subduction of the oceanic domain beneath the Yangtze active margin and the subsequent collision with the Cathaysia passive margin, giving rise to the Jiangnan belt. The suture zone is located in the area of the present NE-trending Jiangshang-Shaoxing fault.

Regarding the calendar, some researchers suggested that the Sibao orogen was a part of the worldwide mid-late Mesoproterozoic-early Neoproterozoic Grenvillian-aged orogenic system associated with the assembly of Rodinia (e.g. Li Z.X et al., 1995, 2002, 2007, 2008; Rivers et al., 2002; Greentree et al., 2006; Li X.H. et al., 2006; Ye et al., 2007; Li W.X. et al., 2008a).

In contrast, other workers considered that the Sibao orogeny lasted between ca.1 and 0.8 Ga, thus was post-Grenville with respect to the timing in the type belt of eastern North America, with an amalgamation completed around 900 Ma (Guo et al., 1985, 1989; Chen et al., 1991; Xu et al., 1992; Shu et al., 1994; Shu and Charvet, 1996; Charvet et al., 1996; Li, 1998; Ye et al., 2007; Li et al., 2008; Chen et al., 2009; Li W.X. et al., 2008a; Li X.H. et al., 2009), between 900 and 830 Ma (Wu et al., 2006; Li XH et al, 2008), between 860-870 and 800 Ma (Wang et al., 2004; Wang et al., 2006, 2007a, 2008), before 820 Ma (e.g., Li, 1999; Zhao and Cawood, 1999; Zheng et al., 2007), or even younger, around 800 Ma (Li et al., 1997; Zhou et al., 2002, 2004; Wang et al., 2008). A diachronous oceanic closure has been suggested by Li et al. (2007, 2009): >1000 Ma to the west and ca. 900-880 Ma at the eastern part of the orogen. Rocks deformed and metamorphosed during the Jiangnan event are unconformably covered by the metasediments of the Nanhua System which is sealing the orogeny.

The development of the Jiangnan orogeny is recorded by: Neoproterozoic magmatic arc, Neoproterozoic ophiolites, HP metamorphism, ductile deformation.

3-1. Neoproterozoic magmatic arc.

Several geochemical studies indicate a magmatic arc setting for volcanic and plutonic rocks, suggesting a subduction beneath the SE border of the Yangtze Block (e.g. Cheng, 1993; Wang et al., 2006; Ye et al., 2007; Li et al., 2009, and ref. therein).

The magmatic arc is mainly represented by: I-type granite, basalt, andesite, rhyolite, tuff and tuffaceous breccias. Those rocks crop out mainly in the Huaiyu area, in the eastern segment of the Jiangnan belt and in western Zhejiang, southern Anhui, and northeastern Jiangxi; at a less extent in Guangdong province. Recent isotopic dating (Fig. 2) yielded ages of: 996 ± 29 Ma (gneissic granite, zircon U-Pb, Liu et al., 2001), 972 ± 8 Ma (rhyolite, SHRIMP zircon U-Pb, Shu et al., 2008b), 913 ± 15 Ma and 905 ± 14 Ma (hornblende-granite, SHRIMP zircon U-Pb, Ye et al., 2007), LA-ICPMS Pb/Pb zircon age of 965±12 Ma on basalt of the Pingshui Formation, (Chen et al., 2009); 893±6 Ma (granodiorite, SHRIMP zircon U-Pb, Yao et al., 2012) and 891±12 Ma (rhyolite, SHRIMP zircon U-Pb, Li et al., 2009). Older age data are: 978±44 Ma by Sm–Nd internal isochron on basalt (Zhang et al., 1990), 846±4 Ma by U-Pb on zircon (Liu et al., 1995).

Regarding the initiation of arc magmatism, the oldest ages are around 970-980 Ma (Zhang et al., 1990; Chen et al., 2009; Gao et al, 2009). But Li et al. (2009) argue that the Tianli schists, considered as a part of the arc, were metamorphosed as early as 1042 ± 7 Ma (Li et al., 2007) and that the NE Jiangxi ophiolites formed in back-arc basin, are dated at ca. 1.0 Ga (Chen et al., 1991); therefore the arc magmatism (and the subduction) started no later than 1.0 Ga. The arc magmatism lasted until ca. 880-905 Ma (Li et al., 2009) to about ca. 840-850 Ma (Liu et al., 1995).

Subduction in the back-arc basin started from at least 968±23 Ma, as suggested by the occurrence of the Xiwan adakitic granites (Li and Li, 2003; Li et al., 2009), and continued until ca. 880 Ma, time of the Xiwan ophiolite obduction onto the continent leading to formation of the 880±19Ma obduction-type biotite granites (Li W.X. et al., 2008a; Li et al., 2009).

3-2. Ophiolitic mélange

An ophiolitic mélange is present in the NE Jiangnan area (Fig. 2), represented by the NE Jiangxi ophiolites. Another one has been advocated near the Jiangshan-Shaoxing Fault, but the related mafic-ultramafic rocks, once regarded as possible Neoproterozoic ophiolitic relics initially linked to the Yangtze–Cathaysia collision history (e.g. Charvet et al., 1999; Shu, 2006; Shu et al., 2006; Wang and Shu, 2007), are now considered as linked to a rifting episode younger than the collision and with a geochemistry different from ophiolites (Li et al., 2009; Charvet et al. 2010; Shu et al., 2011; Shu, 2012).

The NE Jiangxi ophiolitic rocks yielded a SHRIMP zircon U-Pb age of 968 ± 23 Ma (Li et al., 1994) and 970 ± 21 (Gao et al., 2009), Sm-Nd isochron ages of 930 ± 34 Ma (Xu and Qiao, 1989), 935 ± 10 Ma (Chen et al., 1991), 1034 ± 24 Ma (Chen et al., 1991), and 1024 ± 30 Ma (Zhou et al., 1989). The mélange is crosscut by the Shiershan granite that yielded a zircon U-Pb age of 825 ± 3 Ma, providing an upper limit for the ophiolitic mélange (Liu et al., 1995).

3-3. HP metamorphism

A string of glaucophane schists was reported in an amphibolite-facies metamorphic belt of Xiwan area, near Dexing, in Jiangxi Province. From samples collected near Maoqiao and Raoer of Dexing, pressure and temperature were estimated at 0.9-1.3 GPa and 250-450°C (Zhou and Zhou, 1996). K-Ar dating on glaucophane yielded a 866 ± 14 Ma age (Shu et al., 1994; Shu and Charvet, 1996). But, as pointed already by Charvet et al. (1996), this age is likely a bit rejuvenated. Another older age of 901 ± 19 Ma has been determined by $^{40}Ar/^{39}Ar$ dating on amphibole (Xu et al., 1992), with resetting events at around 860 and 790 Ma. Although limited, those HP/LT relics are also arguing in favour of a pre-existing subduction.

3-4. Deformation and greenschist metamorphism.

The ophiolitic mélanges are cropping out within a major shear zone: the NE Jiangxi shear zone. The Northeastern Jiangxi shear zone is 5-10 km wide and shows a NE-trending linear extension along about 250 km. A second one, the Jiangshan-Shaoxing zone, is 20-30 km wide, extending E-W for more than 800 km. Both shear zones show different kinds of mylonite (felsic, granitic, phyllitic) showing usually clear stretching lineation and asymmetric kinematic indicators. The latter suggest two successive phases of deformation: an early top-to-the-SE thrusting and a late sinistral strike-slip shearing (Wang and Mo, 1995; Shu and Charvet, 1996).

The first phase pre-dates the post-collisional granitic plutonism (Shu and Charvet, 1996; Shu, 2012). The second phase, affecting the amalgamated blocks, was accompanied by a widespread regional metamorphism responsible for a very large area of low-grade metamorphic rocks, of greenschist facies, including slate, phyllite, meta-volcanic-rocks, and locally for higher grade garnet biotite schist, amphibole schist and orthogneiss. This sinistral shearing involved the mylonitization of the post-collisional cordierite-bearing Shiersan granite (Shu and Charvet, 1996), dated at 825$\pm$3 Ma by zircon U-Pb method (Liu et al. 1995). This deformation is post-dated by the unconformity of the Nanhuan basal conglomerate, which is now estimated at 750 Ma (Ren et al., 2012).

4. Neoproterozoic collisional to post-collisional events

The oceanic closure and initial thrusting (ophiolitic mélanges) were followed by several events including: syn-collisional to post-collisional magmatism, intra-continental deformation, rifting and general unconformity of the Nanhua system.

4-1. Syn- to post-collisional magmatism

Along the boundary between the Yangtze and Cathaysia blocks, more than 20 granitic plutons occur: Daolinshan of eastern Zhejiang, Xiuning, Shiersan of Western Zhejiang, Xucun of southern Anhui, Jiulingshan of northern Jiangxi, Bendong, Sanfang, Motianling of northern Guizhou (Fig. 2). These granites include frequently cordierite, muscovite, belong to the peraluminous S-type granites, and are dated between 840 and 800 Ma (Liu et al., 1995; Li, 1999; Zeng et al, 2005; Zheng et al., 2007; Zhong et al., 2006). As mentioned above, some of them, like the Shiersan granite, were affected by the ductile sinistral strike-slip shearing along discrete shear zones, suggesting that the last stage of collision was transpressive or the initial stage of collapse occurred in a transtensional regime.

4-2. Rifting

A rifting event, after the South China Block consolidation, is documented by magmatism and sedimentary deposits. The Neoproterozoic is a significant initial rifting period proposed the first time by Gilder et al. (1991).

The magmatic evidence comes firstly from mafic-ultramafic bodies distributed mainly near the Zhenghe-Dapu Fault, in the area of Longquan, Qingyuan, Zhenghe, Sunhchang, Jian'ou, Jianyang (Fig. 2). The wall rocks are quartz schist, gneiss and migmatite. The rock types include: gabbro, diabase, basalt, andesite, and also serpentinite and pyroxenite. According to Shu et al. (2011), the mafic rocks show geochemical characteristics of continental rift basalts and zircon SHRIMP U-Pb analyses yielded rather similar Neoproterozoic ages of 836±7 Ma (gabbro), 841±12 Ma (gabbro), 847±8Ma (gabbro) and 857±7Ma (basalt). Those data are in agreement with some previous ones: SHRIMP zircon U-Pb age of 858+11 Ma on gabbro (Shu et al., 2006), 841 ± 6 Ma zircon SHRIMP U–Pb on the Lipu diorite (Li et al., 2010), 832±7 Ma by 40Ar/39Ar on amphibole grains of mafic schists (Kong et al. 1995), SHRIMP U–Pb zircon age of 795 ± 7 Ma on the diabase of Zhenghe (Shu et al., 2008a), SHRIMP U–Pb zircon ages of 857 ± 0.2 Ma and 853 ± 4 Ma on Jian'ou metabasalt and tuff (Shu et al., 2008b), SHRIMP U–Pb zircon age of 818 + 9 Ma on an alkaline rhyolite of Mamianshan near Zhenghe (Li et al., 2005).

In summary, the ages of such rocks cluster within the range 860-800 Ma. One can notice that there is an overlap in time between the S-type post-collisional granitic intrusions within the core of the belt (840-800 Ma), linked with the collapse of the thickened crust, and the initiation of rifting in South China. The beginning of the process might have included some strike-slip component, in a transpressive to transtensional regime, as suggested by the sinistral shearing affecting the Shiersan granite.

Secondly, several bimodal dykes: diabase and fined-grained granite, crosscut the post-collisional peraluminous plutons, for instance in eastern Zhejiang and northeastern Jiangxi. In the Nanhua rift basin, bimodal volcanic rocks are interlayered with coarse-grained deposits. Basic dykes, trending E-W, intrude the Jiulingshan and yielded zircon U-Pb age of 812+5 Ma (Wang et al., 2006). In Fuyang (eastern Zhejiang), zircon U-Pb ages of 794±9 Ma and 792±5 Ma have been obtained from basalt and rhyolite respectively (Wang and Li, 2003). The bimodal magmatism seems to have stopped at around 760 Ma (Wang and Li, 2003; Li et al., 2005; Shu et al., 2008b; Shu, 2012).

The rifting episode is also recorded in the sedimentary sequences deposited in two different basins: the NE trending Nanhua rift and the N-S trending Kangdian rift basin (Ren and Chen, 1989; Li et al., 2002). For instance, along the suture zone, continental rifting occurred in the Jiangshan-Shaoxing fault zone, leading to the Nanhua rift filled with a thick Nanhuan-Sinian-Lower Paleozoic sequence. There is a conspicuous difference between the litho-tectonic units of this age to the north and to the south of this fault. On the northern side, the sedimentary pile is dominated by shallow sea carbonate-siliceous rocks. On the southern side, a thicker sequence is dominated by sandy slate with limestone lenses (Shu, 2012).

5. Summary of the Neoproterozoic evolution

The evolution from about 1 Ga to ca. 750 Ma can be schematically summarized by the Fig. 3, modified after Charvet et al. (1996) and Shu (2012).

At 1-0.9 Ga, the Yangtze and Cathaysia blocks are separated by an oceanic domain: the South China Ocean, which is consumed by a northwestward subduction beneath the Yangtze block, leading to the Ganzhewan island arc (Shu, 2012) and the Huaiyu back-arc basin.

At ca. 870-860 Ma, the subsequent collision led to the closure of the South China Ocean and the Huaiyu back-arc basin, leading to the emplacement of thrust sheets including ophiolitic mélanges and HP metamorphic rocks.

Between 840 and 800 Ma, late- to post-collisional granitic plutonism took place. The final compressive deformation was partly accommodated by sinistral ductile strike-slip shear. Rifting-linked mafic magmatism began.

Lastly, at around 750 Ma, the rift basin was created and began to be filled with the sedimentary sequence starting with the Nanhuan system.

6. The Early Paleozoic orogeny

The Cathaysia comprises a NE–SW trending orogen, stretching for ca. 2000 km (e.g. Ren et al., 1997, 1999) and possibly extending to the Korean peninsula (e.g. Cluzel et al., 1991; Kim et al., 2006) and to the Indochina Block (Ren, 1991; Carter et al., 2001; Nagy et al., 2001; Roger et al., 2007; Lepvrier et al., 2008; Sajeev et al., 2010; Charvet et al., 2010). This orogen, firstly assigned to the Kwangsian orogeny (Ting, 1929), and then called South China Caledonian Fold Belt (e.g. Huang, 1978), Cathaysian or Huanan Caledonides (e.g. Ren, 1991; Chang, 1996; Charvet et al., 1999), Wuyishan-Yunkaidashan belt (e.g. Zhang et al., 1984), Wuyi-Yunkai tectonic zone (Zhang et al., 1991), Early Paleozoic Orogen of the South China Block (Faure et al., 2009) or Wuyi-Yunkai orogen (Li et al., 2010) in the literature, has been recognized as Early Paleozoic in age due to the angular unconformity, visible in China, between pre-Devonian deformed rocks and Devonian strata (Grabau, 1924; Ting, 1929; Ren, 1964, 1991; Huang et al., 1980; Zhao et al., 1996). It includes Neoproterozoic–Lower Paleozoic non-metamorphic or low grade metamorphic sediments, Paleoproterozoic to Lower Neoproterozoic (Li, 1997; Li Z.X. et al., 2002) high grade metamorphic rocks, migmatites and granitoids. The high grade metamorphic rocks occur mainly in the northeastern segment, including northern Fujian and southern Zhejiang provinces, and in the Nanling zone (e.g. FBGMR, 1985; Shui et al., 1988; Li, 1988, 1989; ZBGMR, 1989; Hu et al., 1991; Gan et al., 1993, 1995; Li et al., 1993; Zhao and Cawood, 1999; Yu et al., 2006).

6-1. Tectonic development: folding and thrusting in an intracontinental orogen

The tectonic history of this Early Paleozoic belt led to controversies in the last two decades, with various interpretations proposed by different workers (see review in Charvet et al., 2010; Shu et al., 2011), distributed basically, since the beginning, within two groups of models: intracontinental orogen (e.g. Ren, 1991, Li, 1998; Charvet et al. 1999, Li and Powell, 2001; Wang et al., 2007b) versus collisional belt (e.g. Wang et al., 1988; Guo et al., 1989; Hsü et al. 1990; Li, 1993). Recently, several authors have provided various robust lines of evidence supporting the interpretation of this belt as an intracontinental orogen, based on structural and petrological studies (Shu, 2006; Shu et al., 2008a; Faure et al., 2009; Li et al., 2010; Charvet et al., 2010; Xu et al., 2011) or independently on detrital zircon U-Pb geochronology (Wang et al., 2010).

Among the subjects of debate, three questions were particularly addressed by workers: i) What was the sedimentary environment in South China during Early Paleozoic, did an oceanic realm exist before the orogeny? ii) What was the geodynamic process that caused the Early Paleozoic tectonic deformation, metamorphism and magmatism, and iii) what was the vergence of structures?

Regarding the first point, new results show that, in continuity with the Sinian (i.e. 0.64-0.54 Ga) deposits, the Cambrian-Ordovician sedimentary sequences suggest a shallow sea environment in South China, although different from the carbonate platform of the Jiangnan domain (Shu, 2012); and the water depth and width of basin during Early Paleozoic show a gradual increase from northeast (Wuyishan) to southwest (Guangxi-Yunnan region) (Shu, 2012). However, for Chen et al. (2012), the timing difference in change of facies during the Ordovician may imply a northward progression of the Kwangsian Orogeny. In addition, the northwestward and westward paleo-current direction suggests that the provenances were located on the eastern and southeastern sides of Cathaysia, supporting the existence of the

South China sea-east China sea continental domain (Shu, 2012). The sedimentological study unravels also the tendency to uplift at the end of the Ordovician, in agreement with the tectono-magmatic history. On the western side, Yangtze foreland, the detrital zircon age spectrum indicates a derivation from the southeast with Precambrian grains derived from the basement of Cathaysia Block and the Early Neoproterozoic Jiangshan-Shaoxing suture (Xu et al., 2012. The restriction of Paleozoic detritus to the latter phases of the Kwangsian orogeny suggests progressive exhumation of the Cathaysia Block, perhaps due to thrusting over the Yangtze Block; the latter remained a site of active sedimentation during orogenesis (Xu et al., 2012).

The sedimentary record argues against the existence of a deep sea environment in the Zhejiang-Fujian-Jiangxi area and, together with the absence of arc volcanic rocks and ophiolitic remnants, against the presence of a Lower Paleozoic oceanic domain in this area.

Regarding the second and third points, structural studies brought new insights on the tectonic development, particularly in the Wuyishan and surrounding areas (Charvet et al., 2010, and ref. therein). The deformation involved the sedimentary sequence from Upper Neoproterozoic to Ordovician strata. But the basement of Cathaysia suffered also intensive reworking through folding, thrusting and magmatism during Early Paleozoic, with large scale anatexis and emplacement of granitoids during the Silurian. This event is well recorded in the Wuyi and Nanling areas (Shu, 2006; Shu et al., 2008b; Faure et al., 2009; Li et al., 2010; Charvet et al., 2010; Zhang et al., 2011; Xu et al., 2011) with the widespread development of slate-phyllite, gneiss, and gneissic granites dated at 440-400 Ma (Shu, 2006; Shu et al., 2008b; Zhang et al., 2009, 2010a,b; Faure et al., 2009; Li et al., 2010; Charvet et al., 2010; Zhang et al., 2011).

Divergent structures were built during the Silurian, verging to the south in the southern part and to the north or northwest in the northern part, together with the development of a regional metamorphism, from low greenschist to locally amphibolites facies and even granulite facies (Yu et al., 2007); the regional metamorphism developed since ca. 453 Ma and reached a peak at around 442 Ma in NW Fujian (Liu et al., 2010). In the Wuyishan, the kinematic indicators (stretching lineation and asymmetric fabrics), suggest a ductile thrusting mainly directed southward, in the low grade meta-sedimentary rocks and in the higher grade reworked basement as well (Charvet et al., 2010). But to the north of the Jiangshan-Shaoxing fault, or to the west of the Ganjiang fault, the folds and thrusts are verging towards the north or northwest (Charvet et al., 2010), Therefore, there is a rather symmetrical geometry, like a fan-like or flower-structure (Charvet et al., 2010; Rong et al., 2010; Shu, 2012). This feature has implications for the geodynamic process responsible for the orogeny.

6-2. Syn- to post-tectonic peraluminous plutonism

Well over 100 post-tectonic granitic bodies were emplaced during the Silurian-Early Devonian (Fig. 4). Most of them belong to peraluminous S-type. The recent geochronological data show that they were intruded mainly between 440 and 390 Ma (Wan et al., 2007, 2010; Wang et al., 2007b; Shu et al., 2008c; Faure et al., 2009; Charvet et al., 2010; Zhang et al., 2010, 2011; Liu et al., 2010; Wang et al., 2011). Some of them show a ductile deformation on their border, with a gneissic to mylonitic fabrics (Shu et al., 1999; Charvet et al., 2010; Xu et al., 2011) suggesting a late tectonic emplacement, possibly synchronous with a general strike-slip environment (Charvet et al., 2010). Their genesis might be due to dehydration melting of Proterozoic crust during the post-crustal thickening relaxation phase of the pre-Devonian orogeny (Li et al., 2010).

6-3. Geodynamic model

If the intracontinental shortening seems to be likely, it may be accommodated in various ways.

Faure et al. (2009) suggested that a possible mechanism could be an intracontinental subduction. However, their very asymmetrical model is facing two difficulties: i) the northward deformation of the northwestern area, the upper plate in the model, is ignored; ii) the metamorphic evolution, of Barrovian type with a pressure peak of 11-12 kb at a temperature of 600°C (Zhao and Cawood, 1999), does not support a subduction setting with some induced HP metamorphism due to a plate going down into the asthenosphere, but rather a crustal thickening due to thrusting. Therefore, a Pyrénées-like model, involving the almost symmetrical shortening of a previous rift, seems preferable (Charvet et al., 2010; Shu, 2012). However some questions remain, regarding for instance the modalities of this crustal thickening and the geodynamic event triggering this intracontinental shortening (see below).

Therefore, the preferred geodynamic evolutionary model, to which I refer the reader, accounting for the Early Paleozoic belt of South China is the one advocated by Charvet et al. (2010), corresponding to a quasi symmetrical shortening of the previous Nanhua rift, involving the inversion of some previous normal faults. Recent works suggest that this geometry could be extended towards the east (Shu , 2012), assuming the existence of a wider continental block including the South China sea-East China sea continental basement.

7. Some pending problems

If the general reconstructions proposed above for the Jiangnan and Early Paleozoic orogenies are compatible with the presently known data set, several questions remain so far unsolved and need further research. I will mention only a few of them.

7-1. Timing and location of the integration of South China into Rodinia.

Several workers argue that the welding of Yangtze and Cathaysia occurred within the general frame of Rodinia assembly (e.g. Li et al., 1995, 1996, 2007, 2008; Ling et al., 2003; Greentree et al., 2006; Xiang and Shu, 2010).

However, there is firstly a problem of timing. If on the western side of Yangtze block, one may find some relics of an event dated at around 1.0 Ga and possibly linked to a Grenville-type orogeny (Yu et al., 2008), the welding of Yangtze and Cathaysia post-dates the Rodinia building by 0.2-0.3 Ga (Ren et al., 2012). Wang et al. (2007a) pointed out also that the termination (after 860 Ma) of the Jinning (Jiangnan) orogeny was significantly younger than the typical Grenvillian orogeny at 1.3–1.0 Ga.

A second problem is the uncertainty about the continents which were the neighbours of South China. Some argue in favour of Australia on the western side (Li et al., 2009) and Siberia on the eastern side (e.g. Li, 1999; Li Z. X. et al., 2008); some others advocate a position between India to the west and Australia to the east (Yu et al., 2008). This issue needs more data.

7-2. Geodynamic process triggering the Early Paleozoic orogeny

If the interpretation of the Early Paleozoic orogeny is correct, corresponding to the intracontinental shortening of the Nanhua rift area, one may wonder about the triggering factor. Was it due to a remote collision of the South China Block with another continent, for instance a greater Indochina or an unknown one now partly represented by some relics in Japan, or more likely the initial Silurian-Devonian collision between South and North China along the Qinling-Dabie suture (Wang et al., 2007b), or the far-field response to the assembly of the Australian–Indian plate with the Cathaysia Block during middle Paleozoic time (Wang et al., 2011)? Was the Nanhua rift a sphenochasm extending to the SW into an oceanic domain allowing a partial deformation in the northeastern part and the continuity of the marine sedimentation from early to Late Paleozoic in the Yunnan area (Ren, 1990; Shu, 2012)? All those points remain unclear for the moment.

7-3. Lower Paleozoic nappes

The existence of thrust sheets has been proposed in many models in order to explain the crustal thickening (Wang et al., 1988; Charvet et al., 1999; Zhao and Cawood, 1999; Shu et al., 2006, 2008b; Li et al., 2010) but poorly documented. Charvet et al. (2010) suggested their existence on a few examples. But, so far, partly due to the outcrop conditions, there is no detailed mapping of such structures. Recognition of superimposition of metamorphic units and mapping of the ductile contacts in areas like the Wuyishan are an important challenge for further understanding of the structural framework.

8. Conclusions

This brief review of the Proterozoic to Early Paleozoic tectonic evolution of South China leads to the following main conclusions.

1) The Jiangnan (Jinning, Sibao) orogeny led to the welding of the Yangzte and Cathaysia blocks, which had previously a different history giving a different pre-Neoproterozoic basement composition.

2) This Jiangnan orogeny was a collisional event, induced by the consumption of an intervening oceanic domain by subduction beneath the Yangzte plate. The evolution involved a volcanic arc on the Yangtze active margin, active from ca. 1000 Ma to ca. 850 Ma, the subsequent collision beginning at around 870-860 Ma and responsible for the emplacement of thrust sheets of ophiolitic mélange (dated around 900 Ma) and blueschists (900-870 Ma), followed by late- to post-collisional granitic plutonism (840-800 Ma).

3) The newly amalgamated South China continental block suffered from rifting, starting around 850 Ma, marked by mafic-ultramafic magmatism until ca. 750 Ma.

4) The Nanhua rift basin evolved with a thick sedimentation in its middle part until the Ordovician.

5) South China was affected by the early Paleozoic orogeny (mainly Silurian), characterized by a strong quasi-symmetrical intracontinental shortening, involving the sedimentary cover of the rift and its margins as well as the basement, leading to crustal thickening.

6) This crustal thickening induced an important anatexis and emplacement of peraluminous granites during the Silurian.

7) Unlike the Jiangnan orogeny, which was of collisional type, the Early Paleozoic one is a bit similar to a Pyrenean intracontinental type.

8) Some pending problems need further research for clarification, for example: the location and timing of integration of South China within Rodinia, the triggering factor of the Early Paleozoic orogeny, the mapping of the contacts bounding the Lower Paleozoic thrust sheets responsible for the crustal thickening.

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Figure captions

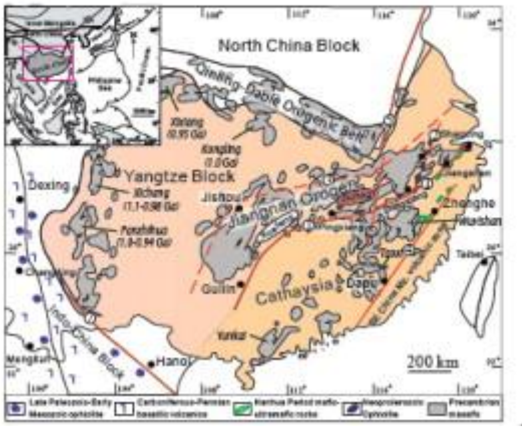

Figure 1. Simplified tectonic framework of South China (after Yu et al., 2008, and Shu, 2012). The outcropping Precambrian metamorphic rocks in the South China Block are represented in grey. The presence of some igneous and metamorphic rocks of Grenville age along the western side of Yangtze block is emphasized. 1, Shaoxing-Jiangshan-Pingxiang fault zone; 2, Dongxiang-Dexing fault zone; 3, The buried fault zone of the northern Jiangnan belt; 4, Zhenghe-Dapu fault zone; 5, Tan-Lu fault zone; 6, Jiangxi River fault zone; 7, Songma fault zone.

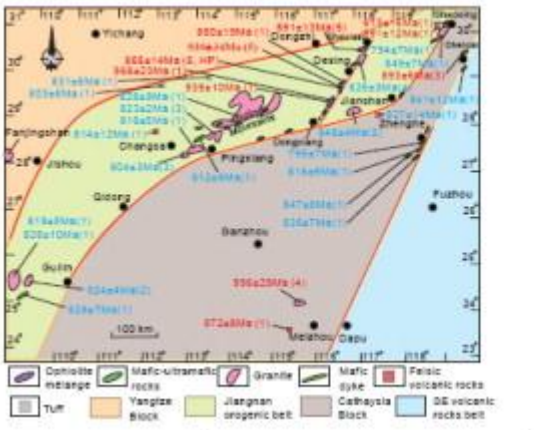

Figure 2. Distribution map of Neoproterozoic igneous rocks and their isotopic dating data (modified after Shu, 2012). The numbers in brackets indicate the isotopic dating methods: 1, SHRIMP zircon U-Pb; 2, SIMS zircon U-Pb; 3, LA-ICPMS zircon U-Pb; 4, ablating zircon

U-Pb; 5, Sm-Nd; 6, K-Ar. Data sources: Xu and Qiao (1989); Zhou et al. (1989); Chen et al. (1991, 2009), Xu et al. (1992); Li et al. (1994, 2005, 2009, 2010); Shu et al. (1994, 2006, 2008a,b, 2011) ; Kong et al. (1995); Liu et al. (1995, 2001); Shu and Charvet (1996); Li (1999); Wang and Li (2003); Zeng et al (2005); Wang et al. (2006); Zhong et al. (2006); Ye et al. (2007); Zheng et al. (2007); Gao et al. (2009); Yao et al. (2012).

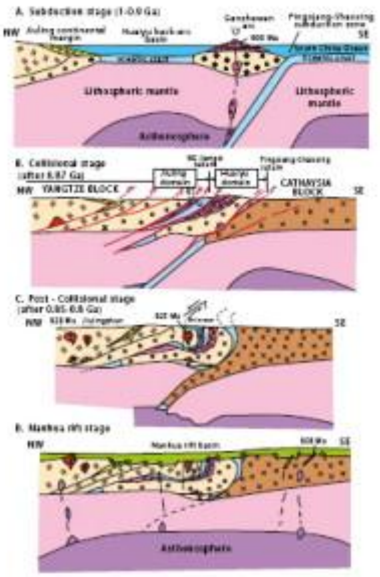

Figure 3. Tectonic evolutionary model of the South China craton during the Neoproterozoic (modified after Charvet et al., 1996, and Shu, 2012).

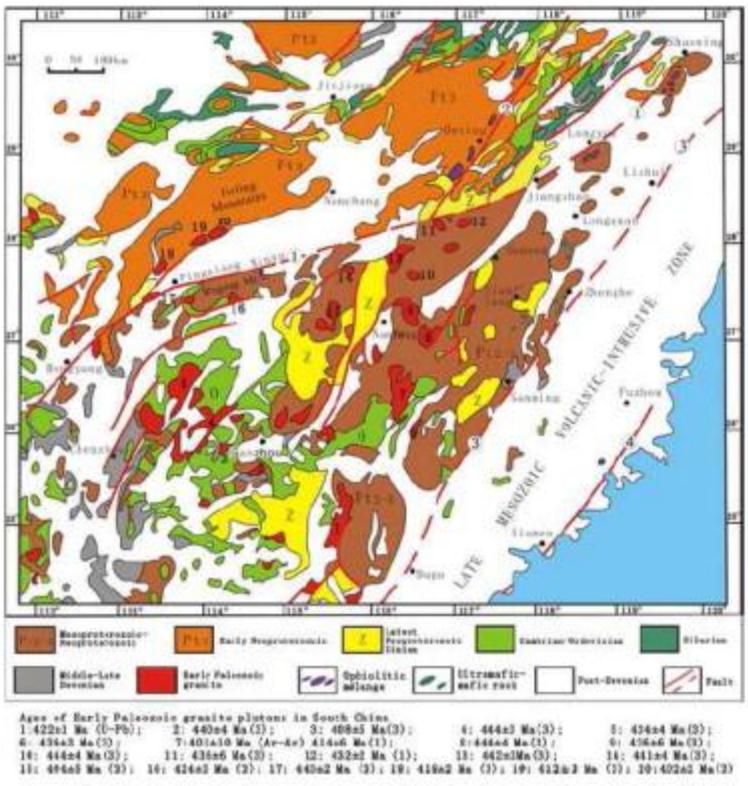

Figure 4. Distribution map of the strata from Neoproterozoic Nanhua Period to Early Paleozoic and of the Early Paleozoic granitoids with isotopic dating data (modified after Shu, 2012). The numbers in brackets indicate the isotopic dating methods as in Fig. 2. Data sources: Shu (2006); Wang Y.J. et al. (2007); Shu et al. (2008c); Wan et al. (2007, 2010); Zhang et al. (2009, 2010a,b, 2011); Faure et al. (2009); Charvet et al. (2010); Li et al. (2010); Liu et al. (2010).